Physics Letters B 738 (2014) 160–165

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Neutrino mass generation and singly charged leptonic exotics in WW events

Hui Luo [a,b,c,d], Ming-xing Luo [a], Kai Wang [a,*], Tao Xu [a], Guohuai Zhu [a]

[a] Zhejiang Institute of Modern Physics, Department of Physics, Zhejiang University, Hangzhou, Zhejiang 310027, China
[b] Dipartimento di Fisica e Astronomia, Università di Padova, Via Marzolo 8, 35131 Padova, Italy
[c] INFN, Sezione di Padova, Via Marzolo 8, 35131 Padova, Italy
[d] SISSA, Via Bonomea 265, 34136 Trieste, Italy

ARTICLE INFO

Article history:
Received 23 July 2014
Received in revised form 15 September 2014
Accepted 19 September 2014
Available online 26 September 2014
Editor: M. Cvetič

ABSTRACT

Current measurement of leptonic WW is significantly higher than the standard model prediction which may accommodate new physics signal that mimics the leptonic decaying W. We investigate a TeV neutrino mass generation model that predicts singly charged leptonic exotics. The collider signature of this model may mimic the leptonic WW search and evade all other searches. With introduction of new $SU(2)_L$ doublet leptons, singly charged exotic leptons $L^\pm$ decay into $L^\pm \to \ell^\pm \phi$ where ϕ is a light singlet scalar of $\mathcal{O}$(MeV) that decays into neutrinos. Drell–Yan production of $L^+L^- \to \ell^+\ell^- + \not{E}_T$ fits leptonic WW searches and $L^\pm L^0 \to \ell^\pm + \not{E}_T$ is completely buried in SM background. In the case of direct lepton from L-decay instead of secondary decay from leptonic $\tau^\pm$, we find the lower mass bound as 125 GeV of such exotic leptons that can be accommodated by the current measurements of WW searches at the LHC. To derive the upper bound, we employ both heavy Higgs boson search of di-lepton plus $\not{E}_T$ final state and leptonic W' search of single lepton plus $\not{E}_T$. Even though heavy Higgs is excluded between 260 and 640 GeV, we find LHC data can still accommodate L between 150 and 300 GeV after giving up the $\eta_{\ell\ell}$ cut. Using the single W' search bound, we can obtain an approximate upper bound as 300 GeV.

Discovery of a 125 GeV Standard Model (SM)-like Higgs boson at the CERN Large Hadron Collider has dramatically improved our knowledge on mass generation for elementary particles in SM [1]. However, clear evidence for physics beyond SM lies in experimental confirmation of sub-eV neutrino masses based on distance/energy dependence measurements in various neutrino oscillation experiments [2]. Being complete neutral under unbroken gauge symmetry $SU(3)_C \times U(1)_{EM}$, neutrino can be Majorana fermion. Moreover, Majorana nature of neutrino also ensures the uniqueness of hyper-charge assignment predicted by gauge anomaly free conditions [3]. The total mass of neutrino states and upper bound on neutrino charge[1] are given in [5].

$$m_{\text{total}} = \sum m_{\nu_i} \lesssim 0.24\ \text{eV}, \qquad q_\nu \lesssim 10^{-15} e. \tag{1}$$

The most elegant proposal of neutrino mass generation is the "see-saw" mechanism [6,7] where the tiny but non-zero neutrino mass arises as a consequence of ultra-high scale ($\mathcal{O}(\Lambda_{GUT})$) physics and the mechanism can be naturally embedded into grand unification framework [7]. In addition, "see-saw" mechanism can naturally account for the observed baryon asymmetry of the universe from WMAP seven year results [8] through "leptogenesis" [9]

$$Y_B \equiv \frac{\rho_B}{s} = (8.82 \pm 0.23) \times 10^{-11}, \tag{2}$$

where ρ_B is the baryon number density and s is the entropy density of the universe.

On the other hand, the "see-saw" mechanism is unlikely to be direct tested experimentally in near future. Heavy singlet fermion with strong Yukawa coupling to the Higgs boson leads to huge correction to the Higgs boson mass as $\delta m_h^2 \simeq m_\nu M_R^3/(2\pi v)^2 \log(q/M_R)$ [10]. Supersymmetry is then inevitable to stabilize the Higgs boson mass while low energy supersymmetry suffers severe direct search bounds at LHC. Thermal leptogenesis also requires lower "see-saw" scale of $\mathcal{O}(10^9$ GeV) with smaller Dirac neutrino Yukawa couplings and large hierarchies in the right-handed neutrino masses [11]. Therefore, there are alternative proposals to generate neutrino masses within TeV.

* Corresponding author.

[1] Based on charge conservation assumption, the neutrino charge bound is further constrained as less than $10^{-21}e$ [4].

http://dx.doi.org/10.1016/j.physletb.2014.09.044
0370-2693/

A 3.5σ deviation has been standing long in muon anomalous magnetic moment, $a_\mu = (g_\mu - 2)/2$ measurement by Brookhaven E821 Experiment [12]

$$\Delta a_\mu \equiv a_\mu^{\rm exp} - a_\mu^{\rm th} = (287 \pm 80) \times 10^{-11}. \tag{3}$$

Even though there also exists large hadronic uncertainty, it may also imply TeV scale extension of SM in the leptonic sector.

Taking an effective field theory approach, neutrino mass in these models can be categorized into higher dimensional operator $(\phi^n/\Lambda^{n+1})\ell\ell hh$ with $n \neq 0$. For cut-off Λ within TeV, ϕ is typically KeV–MeV known as inverse "see-saw" [13,14]. Neutrinoless doublet-beta decay ($0\nu\beta\beta$) experiments played important role in testing the Majorana nature of neutrino however the amplitude is always proportional to the light neutrino mass which is highly suppressed. Similarly, Majorana neutrino of $\mathcal{O}(10^2$ GeV) can also be directly produced at the colliders and lead to like-sign di-lepton signature. The production is through with highly suppressed mixing and Majorana neutrino up to 375 GeV that consistent with $0\nu\beta\beta$-decay bounds can be reached at 14 TeV LHC with 100 fb^{-1} data [15]. The Higgs boson can also decay into sterile neutrino state if the Dirac Yukawa coupling is large and kinematically allowed which may reduce the Higgs decay branching ratio of conventional channels. On the other hand, with di-photon ratio $R_{\gamma\gamma} \gtrsim 1$ in Higgs measurement, there is no enhancement in gluon fusion production and such reduction in BR due to enlarged total width is very unlikely. In some other models, exotics can be produced via gauge interaction with lepton number violation occurring in decay [16]. In particular, doubly charged scalar produced in pair has very distinguished predictions at hadron colliders with negligible background. Two representative models that predict doubly charged scalar are the Zee–Babu model that involves SM singlet scalars and TeV type-II "see-saw" model that involves $SU(2)$ triplet.

On the other hand, if the exotic particles are singly charged or electric neutral, leptonic decaying final states are much similar to the SM W/Z. They can be completely buried in the SM background if the mass range is also close to M_W/M_Z. In particular, W^+W^- pair measurements in both ATLAS and CMS collaborations are significantly larger than the SM prediction [17] while the ZZ measurements are more consistent with the SM predictions. The latest analysis on pure leptonic W^+W^- based on 8 TeV LHC data from ATLAS and CMS is listed in Eq. (4) as

$$\begin{aligned}\sigma_{W^+W^-}^{\rm ATLAS@8TeV} &= 71.4 \pm 1.2({\rm stat.}) \pm 4.5({\rm syst.}) \pm 2.1({\rm lumi.}){\rm pb}\\ \sigma_{W^+W^-}^{\rm CMS@8TeV} &= 69.9 \pm 2.8({\rm stat.}) \pm 5.6({\rm syst.}) \pm 3.1({\rm lumi.}){\rm pb}.\end{aligned} \tag{4}$$

The SM prediction [18] is

$$\sigma_{W^+W^-}^{SM} = 58.7^{+1.0}_{-1.1}({\rm PDF})^{+3.1}_{-2.7}({\rm total}){\rm pb}. \tag{5}$$

At Tevatron experiments, both CDF and DØ also found central values significantly larger than the SM predictions but the error bars were also large [19]. On the other hand, combined analysis of LEP II experiments [20] put stringent bounds on pure leptonic W pair below $\sqrt{s} \leq 206$ GeV with $R_{W^+W^-} = 0.995 \pm 0.008$ which is the ratio of measured production cross section for W^+W^- pair and the SM prediction. There are attempts to explain the excess through new resummation calculation [21] but the excess has also generated several proposals based on supersymmetric models, in particular, light top squark in "natural SUSY" scenario [22]. The colored scalar production rate at 8 TeV LHC is of $\mathcal{O}(10$ pb). With similar leptonic decay branching as Br($W^- \to \ell^-\bar{\nu}$), signal identical visible final states can well fake the leptonic W. Degeneracy condition in spectrum as $M_{\tilde{t}_1} - M_{\tilde{\chi}_1^\pm} \sim \mathcal{O}$(GeV) is also imposed to avoid the visible b-jet. Therefore, the current measurement can well accommodate models predicted singly charged leptonic exotic state, in particular, TeV "see-saw" scenarios (also known as "inverse see-saw" sometimes) for neutrino mass generation. In this paper, we investigate the phenomenology of such singly charged leptonic exotics. The measurement of WW is greater than the theory prediction by $\mathcal{O}(10$ pb) which corresponds to $\mathcal{O}(10 \times (1/3)^2$ pb) production of pure leptonic exotics. Pure leptonic decaying scalar is typically excluded up to the LEP $\sqrt{s} \leq 206$ GeV while Drell–Yan production rate of scalar pair with mass greater than 103 GeV is much smaller than 1 pb and they are much easier to be accommodated in the measurement, for instance, singly charged scalars in a model of radiative neutrino mass generation [23]. If the $\mathcal{O}(10$ pb) excess in WW measurement is completely due to leptonic exotic new physics, one will need larger production. Therefore, in this paper, we focus on inverse "see-saw" (also known as TeV "see-saw") scenarios with singly charged fermionic extension.

Singly charged fermionic states typically arise from new $SU(2)$ double or triplet fermions. In TeV Type-III "see-saw" [24], a singly charged fermion from the $SU(2)_L$ triplet $\Sigma^\pm$ can decay into $\ell + \not{E}$ as

$$\begin{aligned}&\Sigma^+ \to \nu W^+ \quad \text{with } W^+ \to \ell^+\nu,\\ &\Sigma^+ \to \ell^+ Z \quad \text{with } Z \to \nu\bar{\nu}.\end{aligned} \tag{6}$$

However, $\Sigma^\pm\Sigma^0$ production which is larger than $\Sigma^+\Sigma^-$ pair production simultaneously predicts multi-lepton final states which suffer much severe experimental constraints.

We now investigate a model with exotic doublets [14]. A pair of vector-like $SU(2)_L$ doublet fermions L and L^c, an SM singlet N are introduced [14].

$$\mathcal{L} = YhNL + ML^cL + y\phi L^c l + \frac{M_N}{2}NN + \text{h.c.} \tag{7}$$

where l is the $SU(2)$ lepton doublet in SM, h is the SM-like Higgs.

$$L = \begin{pmatrix} L^0 \\ L^- \end{pmatrix}_L \tag{8}$$

ϕ is a singlet scalar with mass of $\mathcal{O}$(MeV) that decays into neutrino thus completely invisible in the detectors.

Light neutrino mass arises as the dimension-seven operator,

$$y^2Y^2\frac{\phi^2}{M_NM^2}llhh, \tag{9}$$

after integrating out the L and N fields. With $\langle\phi\rangle \sim \mathcal{O}$(KeV) and M, M_N being all around $\mathcal{O}(10^2$ GeV), one can easily obtain $m_\nu \sim \mathcal{O}$(eV). Light singlet scalar ϕ participates in flavor physics processes and the y should be carefully chosen to be consistent with flavor physics constraints, for instance, $\mu \to e\gamma$ etc. For precision electroweak measurements, introduction of vector like doublets minimizes the contribution to S-parameter but the Yukawa couplings Y to the SM-like Higgs should be less or equal to 0.2 or so constrained by the T-parameter [14]. On the other hand, these couplings only appear in decays of exotic leptons and do not change the qualitative feature of collider phenomenology.

When $M_N + m_h > M$, $L \to Nh$ decay is kinematically forbidden. The Majorana neutrino N in the model can potentially be tested by neutrinoless double-beta decay as well as the direct production at the hadron colliders. On the other hand, the current bound on $0\nu\beta\beta$-decay [25], $|U_{eN}|^2 \simeq 10^{-5}$ for $M_N \simeq 1$ TeV which is easily satisfied in the model and can at the same time evade the direct search bound at 14 TeV LHC [15].

In the $SU(2)$ limit, L^0 and L^- are nearly degenerate and $L^- \to L^0\pi^-$ decay partial width is extremely small. However, as long as y is not highly suppressed,

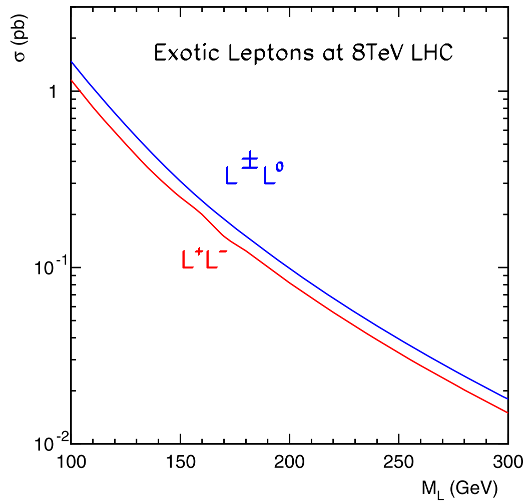

Fig. 1. Drell–Yan production rate for L^+L^- pair $\sigma(pp \to L^+L^-)$ at 8 TeV LHC.

$$L^{\pm} \to \ell^{\pm}\phi, \qquad L^0 \to \nu\phi \tag{10}$$

decay will dominate. The new neutral fermion L^0 is completely invisible. The singly charged exotic lepton decays into SM charged lepton plus $\not{E}_T$ which is identical to leptonic W decay experimentally.

The exotic fermions pair of $L^{\pm}$ and L^0 can be produced at LHC through gauge interaction

$$pp \to L^+L^- \to \ell^+\ell^- + \not{E}_T, \qquad pp \to L^{\pm}L^0 \to \ell^{\pm} + \not{E}_T, \tag{11}$$

where the di-lepton mode can be mis-identified as leptonic W^+W^- while the single-lepton mode is also subject to test at direct search for W'.

To obtain the lower bound from collider bound, we first assume that the excess of $\mathcal{O}(10\text{ pb})$ in WW measurement is completely due to new physics contribution. Fig. 1 shows the production rate for L^+L^- as well as the $L^{\pm}L^0$ at 8 TeV LHC. As argued previously, to explain $\mathcal{O}(10\text{ pb})$ excess for W^+W^-, one needs pure leptonic final states to be of $\mathcal{O}(\text{pb})$.

Lepton universality is well tested at W^+W^- pair measurements and the excess has been observed in all lepton final states e^+e^-, $\mu^+\mu^-$ as well as $e^{\pm}\mu^{\mp}$. Therefore, it also puts stringent constraints on $L^{\pm}$ decay. There are in principle three generations of $L^{\pm}$ and their decays are determined by the y_{ij}. The exotic lepton $L^{\pm}$ decays into electron or muon

$$L_i^{\pm} \to \ell_j^{\pm}\phi \tag{12}$$

through the Yukawa type of interactions $y_{ij}L_i^c l_j \phi$. The structure of Yukawa couplings y_{ij} and the mass spectrum of L_i may in principle affect the neutrino mass spectrum as in Eq. (9). However, this model contains much more freedoms than original "see-saw" mechanism [6] and therefore, y_{ij} and L-mass matrix M are less constrained. To keep the lepton universality, the simplest approach is that the lightest L states dominated decay into $\tau^{\pm}\phi$ and the excess arises from $\tau^{\pm} \to \mu^{\pm}\nu\bar{\nu}$ or $\tau \to e^{\pm}\nu\bar{\nu}$ which makes about 17% of τ decay each. The leptons from τ decay are typically softer than leptons directly from $W^{\pm}$ decay. But, with larger mass, τ-boost from L-decay is more significant than τs from W-decay. In addition, leptons from left-handed polarized τ are also moving in the τ-boosted direction. With all these factors taken into account, the lepton cut survival probability is expected to be higher than leptons from τ decaying from Ws but less than the direct leptons from W decay. Therefore, the production rate can be much larger and the mass can be even lower.

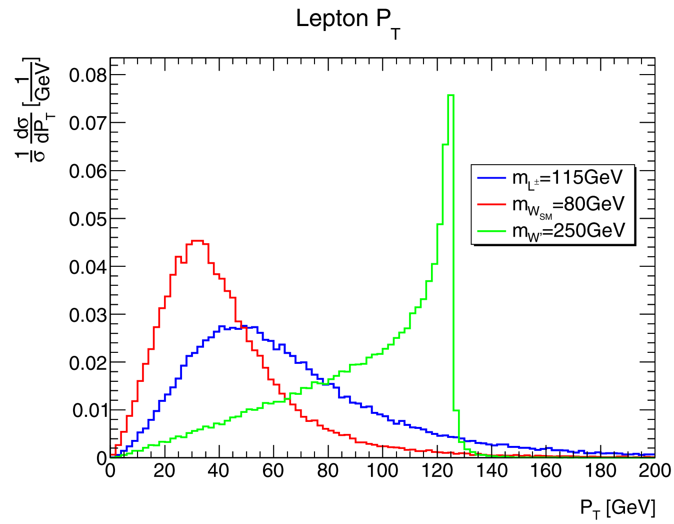

Fig. 2. p_T distribution for leptons from SM W, L of 115 GeV pair production and s-channel W' of 250 GeV.

Therefore, even though with challenge, it is still possible to achieve the universality. To illustrate the feature, in this paper, we discuss an over-simplified scenario with lepton universality for L-decay with decoupled L_2 and L_3 so that $y_{1e} \sim y_{1\mu} \sim y_{1\tau}$. The structure may suffer from constraints from lepton flavor violation tests. The large mixing between different generation leptons may lead to large flavor violation mediated by ϕ and the model may be severely constrained by bounds on $\mu \to e\gamma$ or $\tau \to \mu\gamma$, $\tau \to e\gamma$. But, with the contribution proportional to y^4, this bound can be evaded by making y_{ij} smaller and this is irrelevant to collider phenomenology as long as the L decay is not in meta-stable or long-lived range. On the other hand, as we argued, Eq. (9) connects y_{ij} with neutrino mass matrix. However, even taken y_{ij} as universal, there are as many degrees of freedom as Type-I "see-saw" mechanism and one should be able to accommodate viable neutrino mass matrix just as in Type-I "see-saw" mechanism. If L_2 and L_3 are of 200 GeV, the production rate of L_2, L_3 pairs is only few percent of $L_1^+L_1^-$. W' search around this mass range is much less constrained due to background [5]. With L_2, L_3 decoupled, we neglect the notation i of L_i in the following discussion and focus on the lightest L_i production.

We plot the normalized lepton p_T distribution from $L^{\pm} \to \ell^{\pm}\phi$ decay of L^+L^- pair in Fig. 2 in comparison with leptons in W^+W^- production. In addition, lepton p_T distribution in $L^{\pm}L^0$ production is very similar to that in L^+L^-. For comparison of W' search, we also plot the lepton p_T from single $W' \to \ell^{\pm}\nu$ with $M_{W'} = 250$ GeV. $L^{\pm}$ is slightly heavier than $W^{\pm}$ which results in harder lepton in its decay in comparison with W decay. The $\not{E}_T$ in $L^{\pm}$ decay is also larger. Therefore, the lepton final states from L^+L^- would have higher cuts survival probability. We compare the cut survival probability in L^+L^- with W^+W^- and list them in Table 1 by implementing the ATLAS cuts [17]. Final states are required to have exactly two leptons of opposite sign selected with the ATLAS defined criteria for isolated leptons. The leading lepton is required to have $p_T > 25$ GeV and the sub-leading lepton $p_T > 20$ GeV. To reduce the Drell–Yan di-lepton, $M_{\ell\ell} > 15$ GeV as well as $\mid M_{\ell\ell} - m_Z \mid > 15$ GeV. The study is performed by a modified version of MadEvent [26]. We use the ratio between survival probabilities of two channels, $\epsilon_{W^+W^-}/\epsilon_{L^+L^-}$, to estimate the required production rate for L^+L^-. In principle, $L_i^{\pm} \to \ell_j^{\pm}\phi$ decay strongly depends on Yukawa couplings y_{ij} which play important role in determining neutrino mass spectrum. One can study implications on $L^{\pm}$ decays for different neutrino scenario, inverted

Table 1
Cut survival probability ϵ for leptons decaying from SM $W^\pm$ and $L^\pm$.

Cuts	W^+W^-	105 GeV	110 GeV	115 GeV	120 GeV	125 GeV
No $\not{p}_T$ cut	0.170	0.180	0.174	0.170	0.167	0.160
$\not{p}_T > 45$	0.055	0.120	0.121	0.122	0.125	0.123
$\not{p}_T > 30$	0.096	0.147	0.144	0.143	0.145	0.140

hierarchy or normal hierarchy, etc., by studying correlation between Yukawa couplings y_{ij} and Y_{lm} and neutrino masses. These couplings are also strongly constrained by lepton flavor violation at the same time. To only illustrate the W^+W^- excess feature, we do not make any further assumption on neutrino masses except the estimated mass scale. Naively, the leading order production rate of $\sigma_{L^+L^-}$ can be estimated from

$$\sigma_{LO} \simeq \Delta\sigma_{W^+W^-} \times \mathrm{Br}\big(W^\pm \to \ell^\pm\nu\big) \times \mathrm{Br}\big(W^\pm \to \ell^\pm\nu\big) \times \frac{\epsilon_{W^+W^-}}{\epsilon_{L^+L^-}}/K_{QCD} \tag{13}$$

where K_{QCD} is the perturbative QCD K-factor for this Drell–Yan processes which is about 1.6 for 8 TeV LHC Drell–Yan production of weakly interacting particles of $\mathcal{O}(100\text{ GeV})$. By taking a central $\epsilon_{W^+W^-}/\epsilon_{L^+L^-} \sim 0.5$, the $\sigma_{LO} \sim 0.5$ pb which corresponds to $L^\pm$ of 125 GeV. The efficiencies are only estimated at the parton level and subjected to change when including real detector simulations.

$L^\pm L^0 \to \ell^\pm + \not{E}_T$ mode encounters direct search of W' at the LHC as single lepton plus missing transverse energy. However, single W production with $W^\pm \to \ell^\pm\nu$ at 8 TeV LHC is about 5 nb with error bar 100 pb while $L^\pm L^0$ is only of $\mathcal{O}(\text{pb})$ production rate. Lepton p_T distribution in Fig. 2 also shows significant difference between $L^\pm$ decay from heavy W'. The latter one has a Jacobian peak of $M_{W'}/2$. The leptons from $\mathcal{O}(100\text{ GeV})$ $L^\pm$ state are more like leptons from W decay so $L^\pm L^0$ is completely buried in tails of SM W background [5].

Only left-handed SM lepton participates in L^- decay $L^- \to \tau^-\phi$. On the other hand, the SM W^- decay $W^- \to \tau^-\bar{\nu}$, τ^- is also left-handed polarized. Hence, τ-polarization cannot be used to distinguish the two channels. Since L is not significantly heavier than m_W, distribution like $M_{\ell\ell}$ is also very similar to the SM WW case. $MT2$ reconstruction may not have this resolution to distinguish such 100 GeV-ish resonance from leptonic W. We therefore can conclude that the lower limit for L is 125 GeV given the current measurements at colliders.

To derive an upper bound of L, another relevant search is heavy Higgs search ($H \to WW \to \ell\ell\nu\nu$). The current exclusion with 20 fb^{-1} data at 8 TeV LHC is between 260 and 642 GeV [27]. The production rate for SM-like heavy Higgs with gluon fusion production plus weak boson fusion (VBF) with di-lepton final states $\sigma_{gg+\mathrm{VBF}} \times \mathrm{BR}(H \to WW \to \ell\ell\nu\nu)$ [27] are always larger than the L^+L^- production. For two benchmark points of 300 GeV and 600 GeV SM-like Higgs, the production rate is 290 fb and 50 fb respectively. For the L-mass of 150 GeV and 300 GeV, the corresponding production rate is 210 fb and 15 fb. The heavy Higgs search suffers from severe background of SM WW and $t\bar{t}$ of $\mathcal{O}(100\text{ pb})$. The signal is only at percent of the background and can be easily buried in tails of typical distributions as lepton p_T, $\not{E}_T$ or transverse mass M_T. A very useful handle to distinguish Higgs from SM background is that the two leptons from W decay are moving towards the same direction due to spin-correlation which results in small $\eta_{\ell\ell}$ while the feature is not shared by di-lepton in L^+L^- production. The production of vector-like L^+L^- is basically $1 + \cos^2\theta$ type and leptons ℓ from $L^\pm$ are moving in the same direction. In the LHC searches of heavy Higgs, $\eta_{\ell\ell} < 1$ and $\Delta\phi_{\ell\ell,\not{E}_T} > \pi/2$ are imposed and played important role in the exclusion of heavy Higgs. In Table 3 of [27] for $N_{jet} = 0$, without the cuts over di-lepton angle, the exclusion bound is then released. Since the L^+L^- production is at the beginning smaller than the SM-like Higgs, we argue the heavy Higgs search do not exclude the 150–300 GeV region of L.

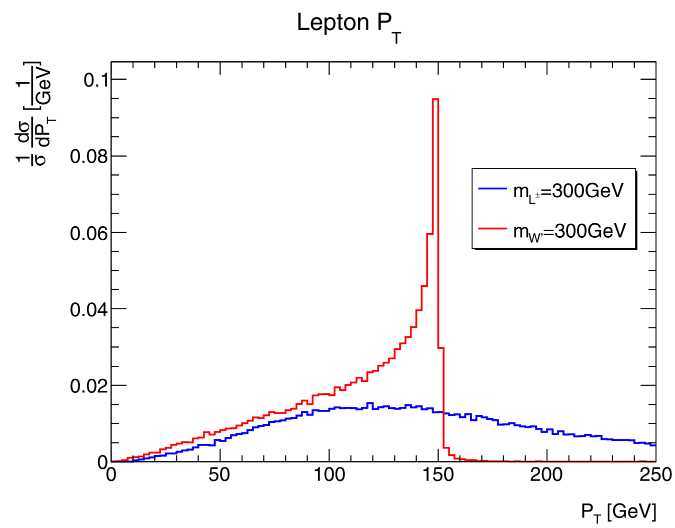

Fig. 3. p_T distribution for leptons from L of 300 GeV pair production and s-channel W' of 300 GeV.

On the other hand, $L^\pm L^0 \to \ell^\pm + \not{E}_T$ production is much larger than the L^+L^- production and the final state is identical to the s-channel leptonic W' search. Therefore, we also take into account the leptonic W' search at colliders. Bound from leptonic W' search at Tevatron is rather weak which is only available for 0.2 fb^{-1} of Tevatron data. The $\sigma(pp \to W') \times \mathrm{BR}(\ell\nu)$ limit for 200–300 GeV W' is between 1.5 pb and 300 fb [28] while the $L^\pm L^0$ production of similar mass range at Tevatron is much smaller than this number. At 8 TeV LHC, $L^\pm L^0$ production for 300 GeV L is 18 fb. The most stringent bound on leptonic W' search comes from the CMS collaboration using 20 fb^{-1} of data at 8 TeV LHC which has pushed the sequential W' to about 3 TeV [29]. Fig. 3 shows the p_T distribution of leptons from L of 300 GeV pair production and s-channel W' of 300 GeV. It is clearly the two signal share almost the same cut survival probability for p_T while the L^+L^0 has even larger cut survival probability for $\not{E}_T$ distribution. At CMS, the observed limit (71 fb) for 300 GeV W' is higher than the expected limit (49 fb) by 20 fb which is way smaller for sequential W' but the $L^\pm L^0$ signature can marginally fit in. The room is much smaller for W' search above 300 GeV. We therefore take the 300 GeV as the upper limit for L.

Finally we study the implications to muon $g-2$ from the model. Muon $g-2$ is a helicity-flipped contribution which is directly correlated to muon mass generation. Since neutrino mass and muon mass usually arise from completely different source, there is no direct correlation between muon $g-2$ and neutrino mass generation. When the light sterile neutrino mixes into the light neutrino state in inverse "see-saw" scenarios, the weak coupling is usually reduced and results in the W-loop contribution to muon $g-2$ which is positive contribution preferred by observation. The exotic lepton $L^\pm$ can couple to left-handed lepton as

$$-iy\phi\overline{(L^-)_R}\mu_L \tag{14}$$

which contributes to muon $g-2$ from ϕ mediated loop and the contribution is [30]

$$\delta a_\mu = \frac{m_\mu^2 y^2}{16\pi^2 M_\phi^2} F_{FFS}\left(M_L^2/M_\phi^2\right) > 0 \tag{15}$$

where

$$F_{FFS}(x) = \frac{1}{6(x-1)^4}\left[x^3 - 6x^2 + 3x + 2 + 6x\ln x\right]. \tag{16}$$

Since $x = M_L^2/M_\phi^2 \gg 1$,

$$F_{FFS}\left(M_L^2/M_\phi^2\right) \sim (1/6)M_\phi^2/M_L^2 \tag{17}$$

therefore we obtain an approximate form in the limit of light ϕ,

$$\delta a_\mu \sim \frac{m_\mu^2 y^2}{96\pi^2 M_L^2}. \tag{18}$$

The contribution to muon $g-2$ is positive which is consistent with the experimental observation. However, with $M_L \simeq 125$–300 GeV, in order to get 200×10^{-11}, y must be larger than 1. As we mentioned, ϕ contribution to flavor violation is inevitable. If the muon related Yukawa is larger between 1 and 10, there must exist a scenario to significantly suppress the electron Yukawa as well as the tau Yukawa which is very un-natural and requires Y and M_N to be tuned to achieve realistic neutrino mass spectrum. Due to this highly fine-tuned structure required by flavor physics, we argue it is very unlikely for this model to explain the muon $g-2$ anomaly.

1. Conclusion

We investigate a TeV neutrino mass generation model that predicts singly charged leptonic exotics. The collider signature of this model may mimic the leptonic WW search and evade all other searches. With introduction of new $SU(2)_L$ doublet leptons, singly charged exotic leptons $L^\pm$ decay into $L^\pm \to \ell^\pm\phi$ where ϕ is a light singlet scalar of $\mathcal{O}$(MeV) that decays into neutrinos. Drell–Yan production of $L^+L^- \to \ell^+\ell^- + \not{E}_T$ fits leptonic WW searches and $L^\pm L^0 \to \ell^\pm + \not{E}_T$ is completely buried in SM background. We focus on the direct lepton from L-decay in the study and find the lower mass bound as 125 GeV of such exotic leptons that can be accommodated by the current measurements of WW searches at the LHC. To derive the upper bound, we employ both heavy Higgs boson search of di-lepton plus $\not{E}_T$ final state and leptonic W' search of single lepton plus $\not{E}_T$. Even though heavy Higgs is excluded between 260 and 640 GeV, we find LHC data can still accommodate L between 150 and 300 GeV after giving up the $\eta_{\ell\ell}$ cut. Using the single W' search bound, we can obtain an approximate upper bound as 300 GeV. Implications of this model to muon $g-2$ are also discussed. Even though the contribution is positive, the required Yukawa coupling y must be larger than the one which is dis-favored by lepton flavor violation experiments.

Acknowledgements

ML is supported by the National Science Foundation of China (11135006) and National Basic Research Program of China (2010CB833000). KW is supported in part, by the Zhejiang University Fundamental Research Funds for the Central Universities (2011QNA3017) and the National Science Foundation of China (11275168, 11422544). GZ is supported in part, by the National Science Foundation of China (11075139, 11375151), Zhejiang University Fundamental Research Funds for the Central Universities (2014QNA3006), the Program for New Century Excellent Talents in University (Grant No. NCET-12-0480). HL is supported by the ERC Advanced Grant no. 267985 (DaMeSyFla).

References

[1] G. Aad, et al., ATLAS Collaboration, Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC, Phys. Lett. B 716 (2012) 1–29, arXiv:1207.7214 [hep-ex];
S. Chatrchyan, et al., CMS Collaboration, Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, Phys. Lett. B 716 (2012) 30, arXiv:1207.7235 [hep-ex].
[2] For example: Y. Fukuda, et al., Super-Kamiokande Collaboration, Phys. Rev. Lett. 81 (1998) 1562, arXiv:hep-ex/9807003;
S. Abe, et al., KamLAND Collaboration, Phys. Rev. Lett. 100 (2008) 221803, arXiv:0801.4589 [hep-ex];
F.P. An, et al., DAYA-BAY Collaboration, Phys. Rev. Lett. 108 (2012) 171803, arXiv:1203.1669 [hep-ex].
[3] M. Fukugita, T. Yanagida, Physics of Neutrinos and Application to Astrophysics, Springer, Berlin, Germany, 2003, 593 pp.
[4] A. Studenikin, I. Tokarev, arXiv:1312.7269 [hep-ph].
[5] J. Beringer, et al., Particle Data Group Collaboration, Phys. Rev. D 86 (2012) 010001.
[6] P. Minkowski, Phys. Lett. B 67 (1977) 421;
T. Yanagida, in: Proc. of the Workshop on the Unified Theory and Baryon Number in the Universe, Tsukuba, Japan, 1979, p. 95;
M. Gell-Mann, P. Ramond, R. Slansky, in: P. van Nieuwenhuizen, et al. (Eds.), Supergravity, North-Holland, 1979, p. 315.
[7] R.N. Mohapatra, G. Senjanovic, Phys. Rev. Lett. 44 (1980) 912.
[8] E. Komatsu, et al., WMAP Collaboration, Astrophys. J. Suppl. Ser. 192 (2011) 18, arXiv:1001.4538 [astro-ph.CO].
[9] M. Fukugita, T. Yanagida, Phys. Lett. B 174 (1986) 45.
[10] F. Vissani, Phys. Rev. D 57 (1998) 7027, arXiv:hep-ph/9709409;
A. de Gouvea, D. Hernandez, T.M.P. Tait, Phys. Rev. D 89 (2014) 115005, arXiv:1402.2658 [hep-ph].
[11] W. Buchmuller, M. Plumacher, Int. J. Mod. Phys. A 15 (2000) 5047, arXiv:hep-ph/0007176.
[12] G.W. Bennett, et al., Muon G-2 Collaboration, Phys. Rev. D 73 (2006) 072003, arXiv:hep-ex/0602035.
[13] J. Schechter, J.W.F. Valle, Phys. Rev. D 22 (1980) 2227;
D. Wyler, L. Wolfenstein, Nucl. Phys. B 218 (1983) 205;
C.N. Leung, S.T. Petcov, Phys. Lett. B 125 (1983) 461;
R.N. Mohapatra, J.W.F. Valle, Phys. Rev. D 34 (1986) 1642;
S.C. Park, K. Wang, Phys. Lett. B 701 (2011) 107, arXiv:1011.3621 [hep-ph].
[14] L.J. Hall, H. Murayama, G. Perez, Phys. Rev. Lett. 95 (2005) 111301, arXiv:hep-ph/0504248.
[15] A. Atre, T. Han, S. Pascoli, B. Zhang, J. High Energy Phys. 0905 (2009) 030, arXiv:0901.3589 [hep-ph].
[16] T. Han, B. Mukhopadhyaya, Z. Si, K. Wang, Phys. Rev. D 76 (2007) 075013, arXiv:0706.0441 [hep-ph];
P. Fileviez Perez, T. Han, G.-y. Huang, T. Li, K. Wang, Phys. Rev. D 78 (2008) 015018, arXiv:0805.3536 [hep-ph].
[17] The ATLAS Collaboration, ATLAS-CONF-2014-033;
S. Chatrchyan, et al., CMS Collaboration, Phys. Lett. B 721 (2013) 190, arXiv:1301.4698 [hep-ex].
[18] V.S. Fadin, L.N. Lipatov, A.D. Martin, M. Melles, Phys. Rev. D 61 (2000) 094002, arXiv:hep-ph/9910338;
B. Jager, C. Oleari, D. Zeppenfeld, J. High Energy Phys. 0607 (2006) 015, arXiv:hep-ph/0603177;
A. Bierweiler, T. Kasprzik, J.H. Kühn, S. Uccirati, J. High Energy Phys. 1211 (2012) 093, arXiv:1208.3147 [hep-ph];
S. Dawson, I.M. Lewis, M. Zeng, Phys. Rev. D 88 (5) (2013) 054028, arXiv:1307.3249.
[19] V.M. Abazov, et al., D0 Collaboration, Phys. Rev. Lett. 103 (2009) 191801, arXiv:0904.0673 [hep-ex];
T. Aaltonen, et al., CDF Collaboration, Phys. Rev. D 82 (2010) 112001, arXiv:1008.4404 [hep-ex].
[20] LEP and ALEPH and DELPHI and L3 and OPAL and LEP Electroweak Working Group and SLD Electroweak Group and SLD Heavy Flavor Group Collaborations, arXiv:hep-ex/0312023.
[21] P. Meade, H. Ramani, M. Zeng, arXiv:1407.4481 [hep-ph];
P. Jaiswal, T. Okui, arXiv:1407.4537 [hep-ph].
[22] D. Curtin, P. Jaiswal, P. Meade, Phys. Rev. D 87 (3) (2013) 031701, arXiv:1206.6888 [hep-ph];
K. Rolbiecki, K. Sakurai, J. High Energy Phys. 1309 (2013) 004, arXiv:1303.5696 [hep-ph];
D. Curtin, P. Jaiswal, P. Meade, P.-J. Tien, J. High Energy Phys. 1308 (2013) 068, arXiv:1304.7011 [hep-ph];

D. Curtin, P. Meade, P.-J. Tien, arXiv:1406.0848 [hep-ph];
J.S. Kim, K. Rolbiecki, K. Sakurai, J. Tattersall, arXiv:1406.0858 [hep-ph];
M. Czakon, A. Mitov, M. Papucci, J.T. Ruderman, A. Weiler, arXiv:1407.1043 [hep-ph].

[23] E. Ma, Phys. Rev. D 73 (2006) 077301, arXiv:hep-ph/0601225.

[24] R. Foot, H. Lew, X.G. He, G.C. Joshi, Z. Phys. C 44 (1989) 441;
For Example: A. Arhrib, B. Bajc, D.K. Ghosh, T. Han, G.-Y. Huang, I. Puljak, G. Senjanovic, Phys. Rev. D 82 (2010) 053004, arXiv:0904.2390 [hep-ph];
T. Li, X.-G. He, Phys. Rev. D 80 (2009) 093003, arXiv:0907.4193 [hep-ph].

[25] A. Faessler, M. Gonzalez, S. Kovalenko, F. Simkovic, arXiv:1408.6077 [hep-ph].

[26] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, T. Stelzer, J. High Energy Phys. 1106 (2011) 128, arXiv:1106.0522 [hep-ph].

[27] The ATLAS Collaboration, ATLAS-CONF-2013-067.

[28] A. Abulencia, et al., CDF Collaboration, Phys. Rev. D 75 (2007) 091101, arXiv:hep-ex/0611022.

[29] CMS Collaboration, CMS-PAS-EXO-12-060.

[30] A. Freitas, J. Lykken, S. Kell, S. Westhoff, J. High Energy Phys. 1405 (2014) 145, arXiv:1402.7065 [hep-ph].